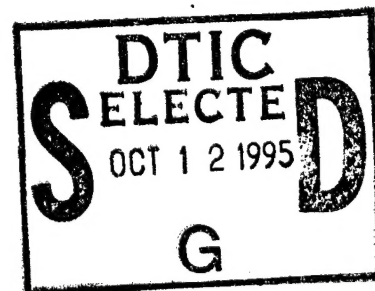


ARMY RESEARCH LABORATORY



# Fourier Transform Raman (FTR) Spectroscopy of Some Energetic Materials and Propellant Formulations II

Nicholas F. Fell  
Jeffrey M. Widder  
Stephen V. Medlin  
Jeffrey B. Morris  
Rose A. Pesce-Rodriguez  
Kevin L. McNesby



ARL-TR-843

August 1995

19951011 066

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.

DTIC QUALITY INSPECTED 8

## **NOTICES**

**Destroy this report when it is no longer needed. DO NOT return it to the originator.**

**Additional copies of this report may be obtained from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.**

**The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.**

**The use of trade names or manufacturers' names in this report does not constitute indorsement of any commercial product.**

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE August 1995	3. REPORT TYPE AND DATES COVERED Final, January-April 1995		
4. TITLE AND SUBTITLE Fourier Transform Raman (FTR) Spectroscopy of Some Energetic Materials and Propellant Formulations II		5. FUNDING NUMBERS PR: 1L161102AH43		
6. AUTHOR(S) Nicholas F. Fell, Jeffrey M. Widder, Stephen V. Medlin, Jeffrey B. Morris, Rose A. Pesce-Rodriguez, and Kevin L. McNesby				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: AMSRL-WT-PC Aberdeen Proving Ground, MD 21005-5066		8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-843		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSORING/MONITORING AGENCY REPORT NUMBER		
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.		12b. DISTRIBUTION CODE		
13. ABSTRACT (Maximum 200 words) Fourier transform Raman (FTR) spectroscopy employing near infrared (NIR) laser radiation at $9,394.5\text{ cm}^{-1}$ is used to characterize neat energetic materials and several propellant formulations. Raman spectra are reported over the region from $100\text{ cm}^{-1}$ to $3,000\text{ cm}^{-1}$ , relative to the Rayleigh line. The technique is extended to the study of crystalline components of propellant formulations during heating. The utility of the technique in determining the principal crystalline ingredient in a propellant formulation is demonstrated.				
14. SUBJECT TERMS Raman spectroscopy, energetic materials			15. NUMBER OF PAGES 21	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

INTENTIONALLY LEFT BLANK.

## ACKNOWLEDGMENT

Support is acknowledged from the National Research Council Postdoctoral Associateship Program and the Strategic Environmental Research and Development Program (SERDP) of the U.S. Department of Defense (DOD). Thanks are expressed to Dr. Monte Chawla of Atlas Wireline Services, Inc., for providing the samples of HNS and of the Chinese propellant formulation.

Accession For	
NTIS	CRA&I <input checked="checked" type="checkbox"/>
DTIC	TAB <input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification .....	
By .....	
Distribution /	
Availability Codes	
Dist	Avail and/or Special
A-1	

**INTENTIONALLY LEFT BLANK.**

## TABLE OF CONTENTS

	<u>Page</u>
ACKNOWLEDGMENT .....	iii
LIST OF FIGURES .....	vii
1. INTRODUCTION .....	1
2. EXPERIMENTAL .....	1
3. RESULTS AND DISCUSSION .....	3
3.1 Neat Energetic Materials .....	3
3.2 Applications to Propellant Analysis .....	6
4. CONCLUSION .....	11
5. REFERENCES .....	13
DISTRIBUTION LIST .....	15

INTENTIONALLY LEFT BLANK.



## LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1. Simple diagram of the experimental apparatus used in these experiments .....	2
2. The FTR spectra of RDX and HMX .....	4
3. The FTR spectra of PETN and NQ .....	5
4. The FTR spectra of ADN and TNT .....	5
5. The FTR spectra of CL-20 and TNAZ .....	7
6. The FTR spectra of HNS and pDNPA .....	7
7. The FTR spectra of DMNA and NC .....	8
8. The FTR spectra of GAP and AP .....	8
9. The FTR spectra of RDX, HMX, and XM39 .....	9
10. The FTR spectra of RDX, XM39, and a propellant formulation believed to have been manufactured in mainland China .....	10
11. The FTR spectra of XM39 as it is heated from 297 K to 458 K .....	10

INTENTIONALLY LEFT BLANK.

## 1. INTRODUCTION

Fourier transform Raman (FTR) spectroscopy using near infrared (NIR) laser light as the scattering source has been shown to be useful in the identification of crystalline components of propellant formulations (Akhaven 1991). The ease with which many principal components of propellant formulations may be identified is due to the generally good scattering characteristics of crystalline energetic materials combined with the poor scattering characteristics of most plasticizers and binders. Although using NIR laser light as the scattering source limits the signal intensity compared to that obtained using visible laser light scattering, the lack of fluorescence interference when working in the NIR spectral region often outweighs this disadvantage. If a disadvantage exists in trying to measure Raman spectra of propellant formulations using NIR laser scattering, it is that most colored formulations will absorb the laser light and combust. Fortunately, most crystalline neat energetic materials are not colored, so the technique can often yield excellent results.

Recently we published a short paper consisting of Raman spectra of several neat energetic materials and several propellant formulations (McNesby et al. 1994). It was our goal at the time to have that paper be the first in a series to aid in the assembly of a Raman spectral database of energetic materials and propellant formulations. Since that time, modifications to our instrument have enabled coverage of a broader spectral range, so we have remeasured the spectra of most of the neat energetic materials reported in the first paper, added several more spectra of neat energetic materials not measured, and also have included some new energetic formulations and techniques. We hope most readers find this report a useful continuation of our initial effort towards the characterization of energetic materials by FTR spectroscopy.

## 2. EXPERIMENTAL

The experimental apparatus has been described previously (McNesby et al. 1994). Briefly, the equipment employed in these experiments consists of a Bomem DA-8.02 Fourier transform spectrometer to which a Raman accessory has been added. Incident radiation is provided by a Quantronix Series 100 Nd:YAG laser. A simple sketch of the experimental apparatus is shown in Figure 1. Raman-shifted radiation is collected using a back-scattering geometry and is detected after filtering and interferometer modulation using a liquid nitrogen-cooled InGaAs detector. Recently the interference filters used to exclude the Rayleigh line at a wavelength of  $1.06\text{ }\mu\text{m}$  ( $9,394.5\text{ cm}^{-1}$ ) were replaced by holographic notch

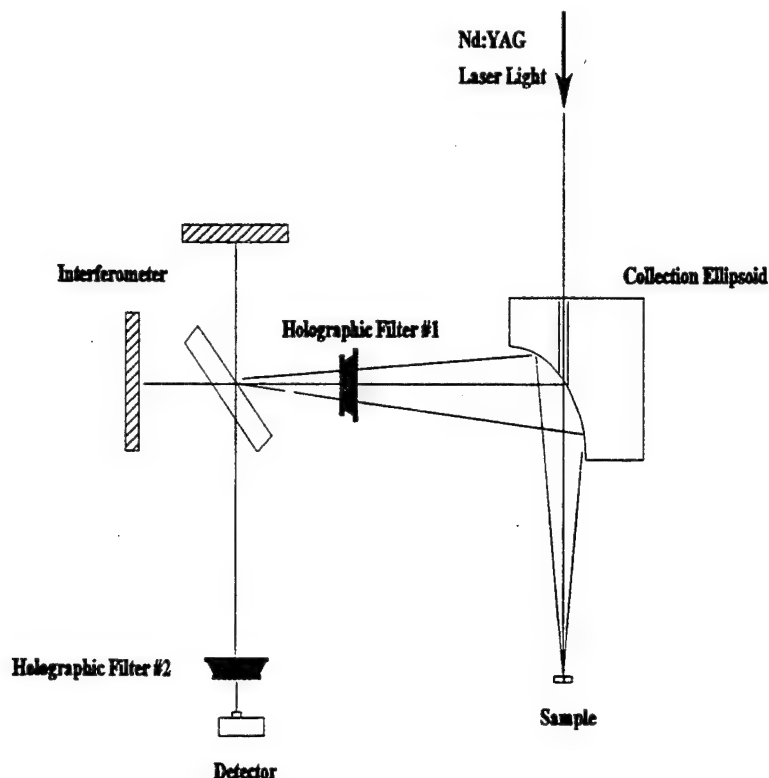


Figure 1. Simple diagram of the experimental apparatus used in these experiments.

filters (Kaiser Optical). This enabled measurement of Raman transitions shifted from 100 to 3,000  $\text{cm}^{-1}$  with respect to the Rayleigh line (the previous spectral range of the instrument was from 400 to 3,000  $\text{cm}^{-1}$ ). Also, we are able to observe anti-Stokes lines shifted from the Rayleigh line by 150 to 600  $\text{cm}^{-1}$ .

All spectra reported here were measured at 4  $\text{cm}^{-1}$  resolution using coaddition of 256 scans. Incident laser power was 400 mW. Scan time to collect each spectrum was 11 min. All spectra were measured using the back scattering arrangement shown in Figure 1. Neat samples of energetic materials were placed in 1-mm i.d. glass capillary tubes, and the Nd:YAG laser focused on the surface of the tube. Propellant formulations, when in the form of cylindrical grains, were placed in a temperature-variable holder whose position could be maintained from run to run. The Nd:YAG laser light was then focused on a flat surface of the grain created by cleaving the grain normal to its longitudinal axis. Powdered propellant formulations were placed in a 5-mm-diameter glass tube that was then placed in a sample spinner (Princeton Photonics) operated at 2,400 rpm to minimize heating effects. The Nd:YAG laser was then

focused on the surface of the spinning tube. No correction was made to any of the spectra to account for responsivity of the detector, interferometer, or filters used in the experiments. For the spectra of neat energetic materials reported here, the intense feature at zero Raman shift is due to Rayleigh scatter that was not fully attenuated by the holographic filters. The intense ringing about zero shift is a manifestation of the intensity of the Rayleigh scatter entering the interferometer and the boxcar apodization used in the Fourier transformation of the raw data (Griffith and de Haseth 1986). Samples of HNS and of the Chinese propellant formulation were provided by Atlas Wireline Services, Inc. All other propellant samples used in these experiments were obtained from in-house sources.

### 3. RESULTS AND DISCUSSION

3.1 Neat Energetic Materials. Table 1 shows a summary of the energetic materials whose FTR spectra are described in this report. Figure 2 shows the FTR spectra of the most common nitramine energetic material, cyclotrimethylenetrinitramine (RDX), and of the eight-membered ring homolog, cyclotetramethylenetetranitramine (HMX). There are several interesting features in these spectra. First, unlike our previously published spectra, we are now able to observe in each spectrum vibrational transitions to within  $100\text{ cm}^{-1}$  of the Rayleigh line. Vibrational transitions due to ring deformations in RDX and HMX, occurring at Raman shifts of from  $100$  to  $400\text{ cm}^{-1}$ , were not measurable in our laboratory prior to installation of the holographic rejection filters. Crystal lattice modes (Goetz and Brill 1979) in nitramine crystals, which occur below  $100\text{ cm}^{-1}$ , fall within the "notch" of the holographic filters so are not observable. In the FTR spectrum of HMX, an intense peak is observed that is centered at a Raman shift of  $150\text{ cm}^{-1}$ . This peak is close to the intensity of the most intense ring stretch features that occur in HMX from  $800$  to  $1,000\text{ cm}^{-1}$ .

Figure 3 shows the spectrum of the nitrate ester pentaerythritol tetranitrate (PETN), a common ingredient in some commercial explosives. Also shown is the FTR spectrum of nitroguanidine (NQ). The N-H stretch in nitroguanidine at a Raman shift of approximately  $3,200\text{ cm}^{-1}$  is not observed since it occurs beyond the range of the InGaAs detector. Figure 4 shows the spectrum of ammonium dinitramide (ADN), an oxidizer whose use is rapidly expanding within the propellant community, and of trinitrotoluene (TNT). In both of these spectra, features below  $400\text{ cm}^{-1}$  are among the most intense in each spectrum. For the spectrum of TNT, the slightly elevated baseline is caused by sample heating during measurement of the spectrum since neat TNT is light yellow in color and absorbs some of the incident Nd:YAG laser radiation.

Table 1. Energetic Materials Used in These Experiments

Energetic Material	Laser Power (mW)	Composition
RDX	400	neat
HMX	400	neat
PETN	400	neat
NQ	400	neat
ADN	400	neat
TNT	400	neat
CL-20	400	neat
TNAZ	400	neat
HNS	400	neat
pDNPA	400	neat
NC	400	neat
DMNA	400	neat
AP	400	neat
GAP	400	neat
XM39	400	76% RDX, 24% binders and plasticizers

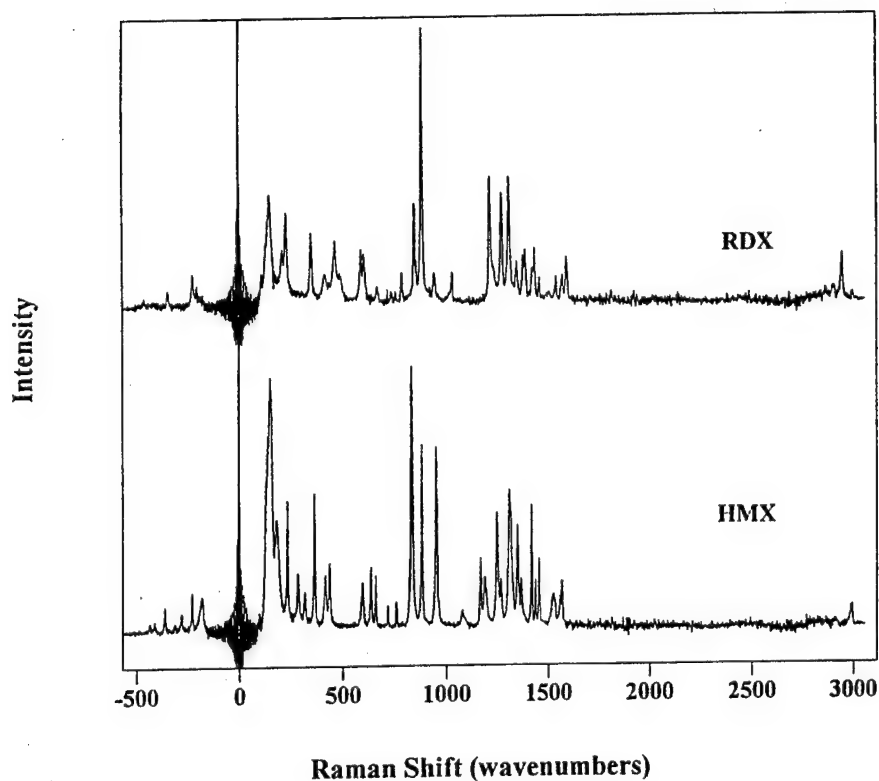


Figure 2. The FTR spectra of RDX and HMX.

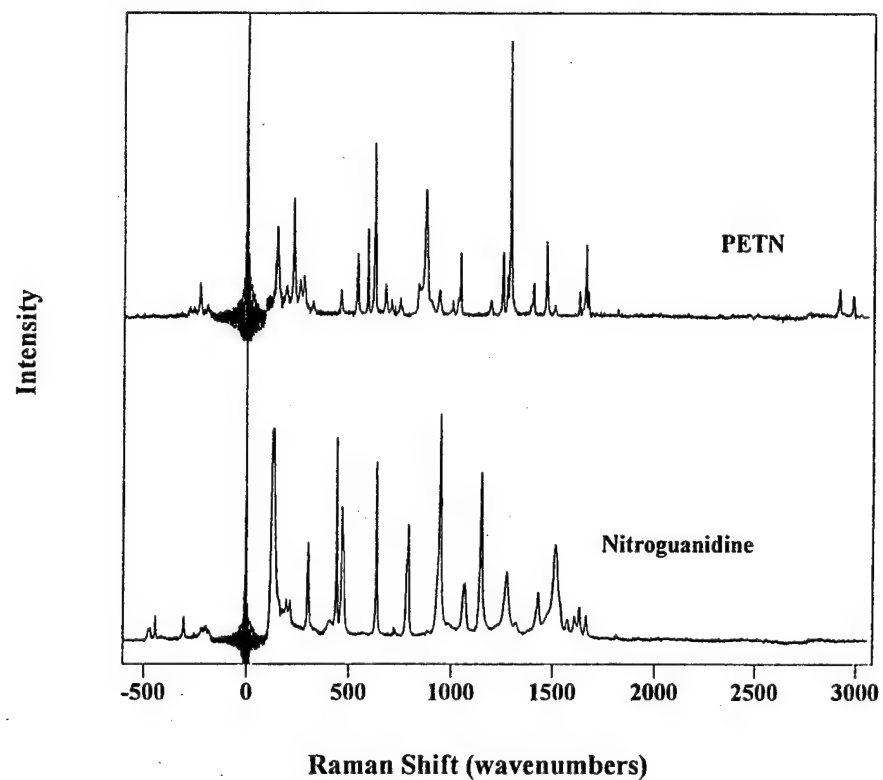


Figure 3. The FTR spectra of PETN and NQ.

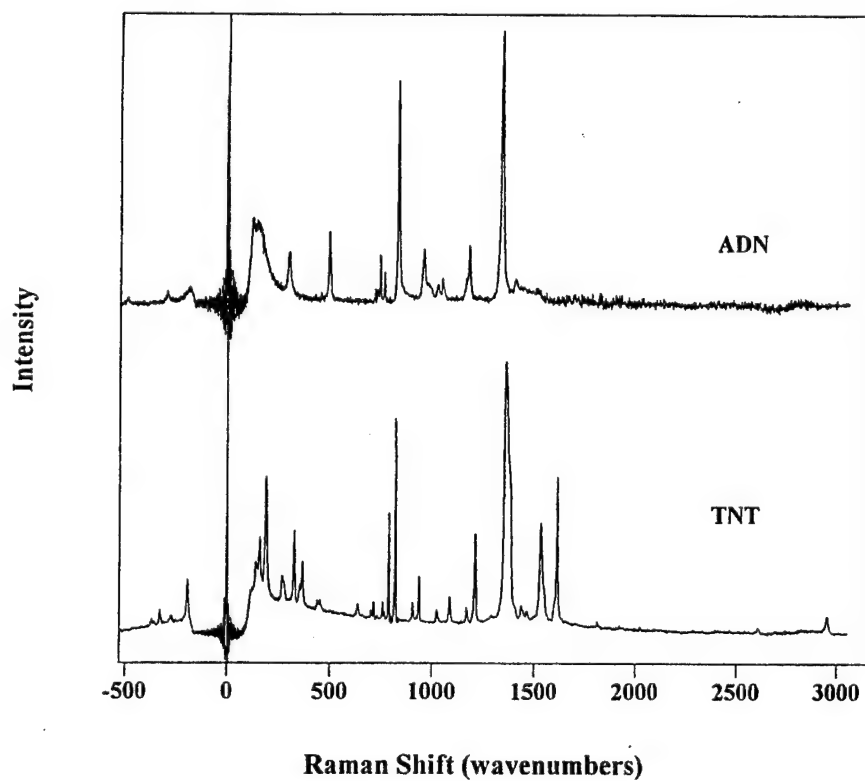


Figure 4. The FTR spectra of ADN and TNT.

Figure 5 shows the spectra of beta-hexanitrohexaazaisowurtzitane (CL-20, previously reported using the alternate name b-HNIW), an energetic caged nitramine, and 1, 3, 3-trinitroazetidine (TNAZ), a recently developed energetic nitramine containing a germinal dinitro group. Figure 6 shows the spectrum of hexanitrostilbene (HNS), an industrial explosive used in high-temperature applications, and polydinitropropyladapate (pDNPA), an energetic polymeric binder used in some propellant formulations. Both spectra were measured using incident radiation at a power of 400 mW, although the signal-to-noise ratio in the spectrum of HNS is superior to that of the spectrum of pDNPA. These spectra illustrate the general observation that crystalline energetic materials are better Raman scatterers than polymeric energetic materials (McNesby et al. 1994).

Figure 7 shows the FTR spectra of dimethylnitramine (DMNA), a simple energetic nitramine, and nitrocellulose (NC). While both spectra were measured using the same incident laser power and using the same sampling technique (1-mm i.d. capillary tube), the signal-to-noise ratio in the spectrum of crystalline DMNA is superior to that of polymeric nitrocellulose. Both samples were in the form of white powders. Figure 8 shows the FTR spectra of glycidyl azide polymer (GAP), an energetic binder, and ammonium perchlorate (AP), an important oxidizer for many composite propellant formulations, and the only inorganic energetic material included in this study. Again, it may be seen from Figure 8 that the FTR spectrum of the crystalline material (AP) has a higher signal-to-noise ratio than the polymeric GAP.

**3.2 Applications to Propellant Analysis.** Figure 9 shows the FTR spectra of RDX, HMX, and XM39, a propellant formulation whose principal ingredient is RDX. The spectrum of XM39 is an illustration of the utility of FTR spectroscopy for energetic material characterization in general and for identification of nitramine-based explosives in particular. While the spectra of RDX and HMX in Figure 2 were measured using neat powdered samples in capillary tubes, the spectrum of XM39 was measured by scattering the Nd:YAG laser light off of the interior surface of a cleaved propellant grain. Even with this simple sampling technique, assignment of RDX as the principal crystalline energetic ingredient in XM39 is unambiguous. Shown in the spectrum of XM39 is evidence of HMX "impurity" in the formulation. HMX is a normal by-product of RDX synthesis in most domestically produced RDX. Also shown in the spectrum of XM39 is the increased intensity (relative to neat RDX) of the feature near  $150\text{ cm}^{-1}$ . This increased intensity (see Figure 2) may be due to the small HMX "impurity" in domestically manufactured RDX.



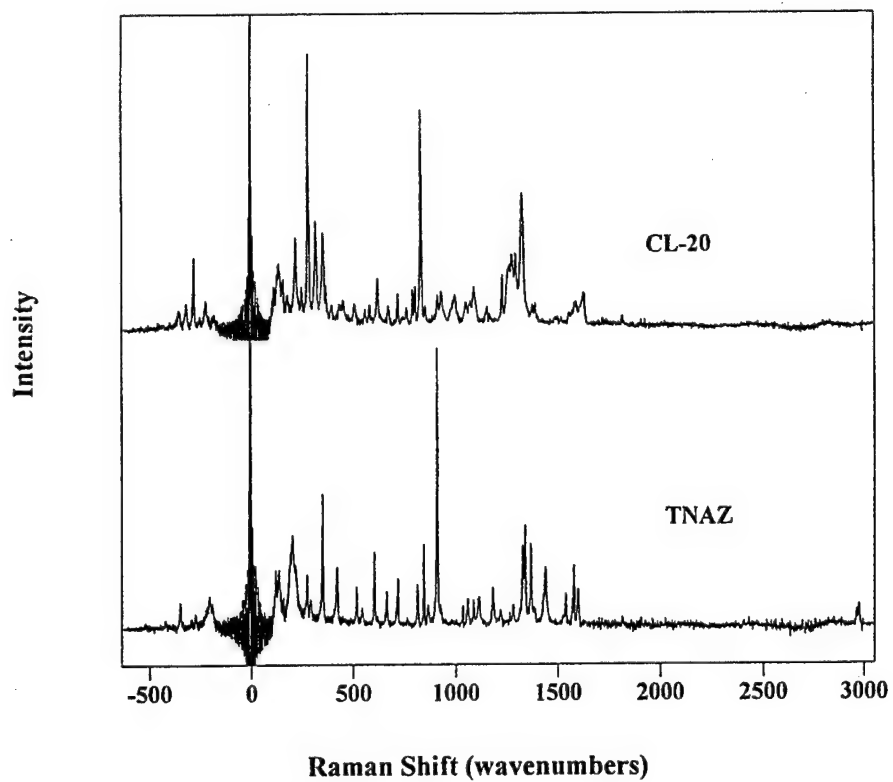


Figure 5. The FTR spectra of CL-20 and TNAZ.

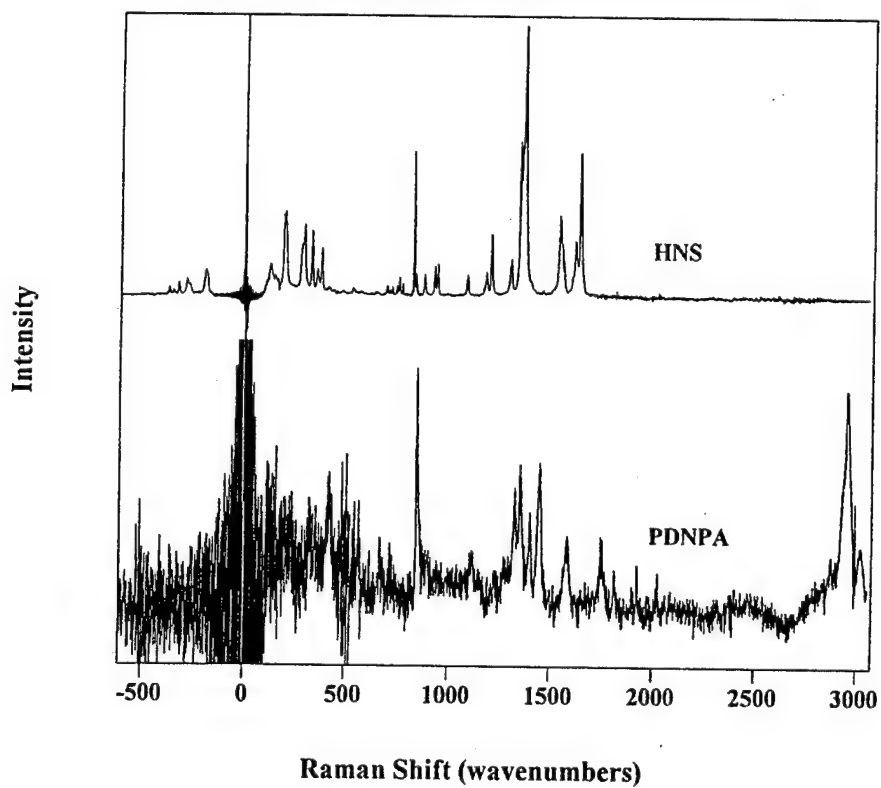


Figure 6. The FTR spectra of HNS and pDNPA.

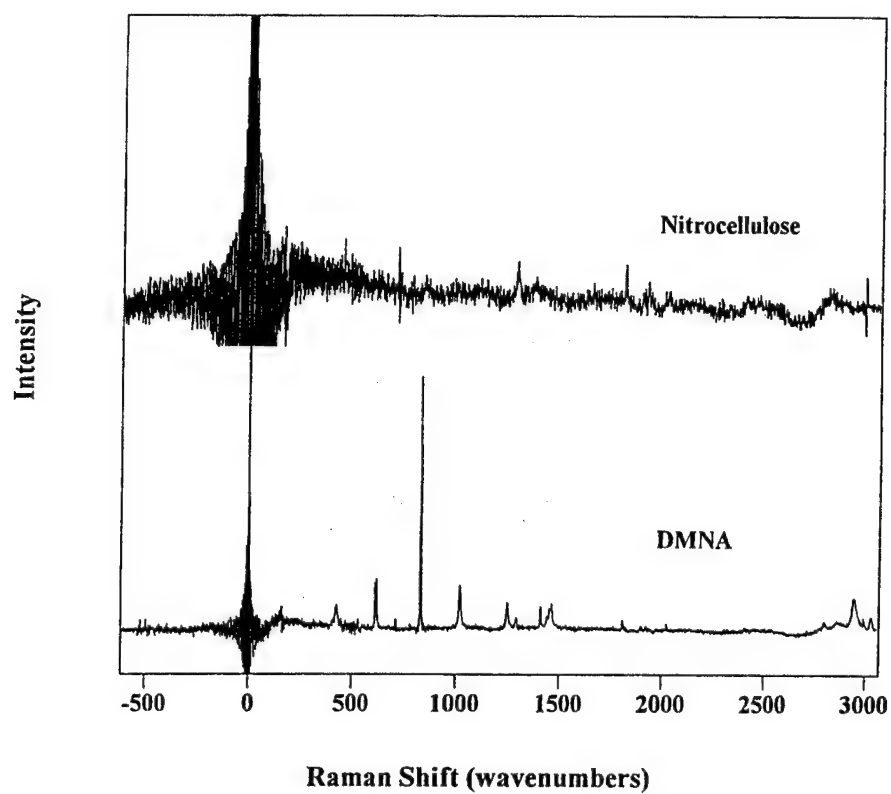


Figure 7. The FTR spectra of DMNA and NC.

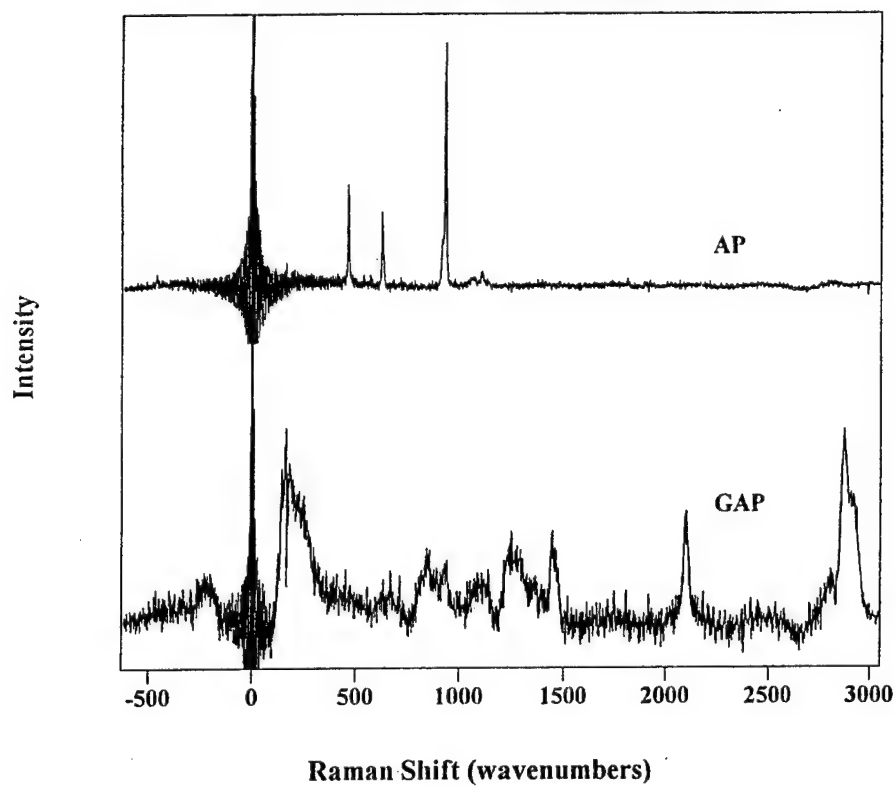


Figure 8. The FTR spectra of GAP and AP.

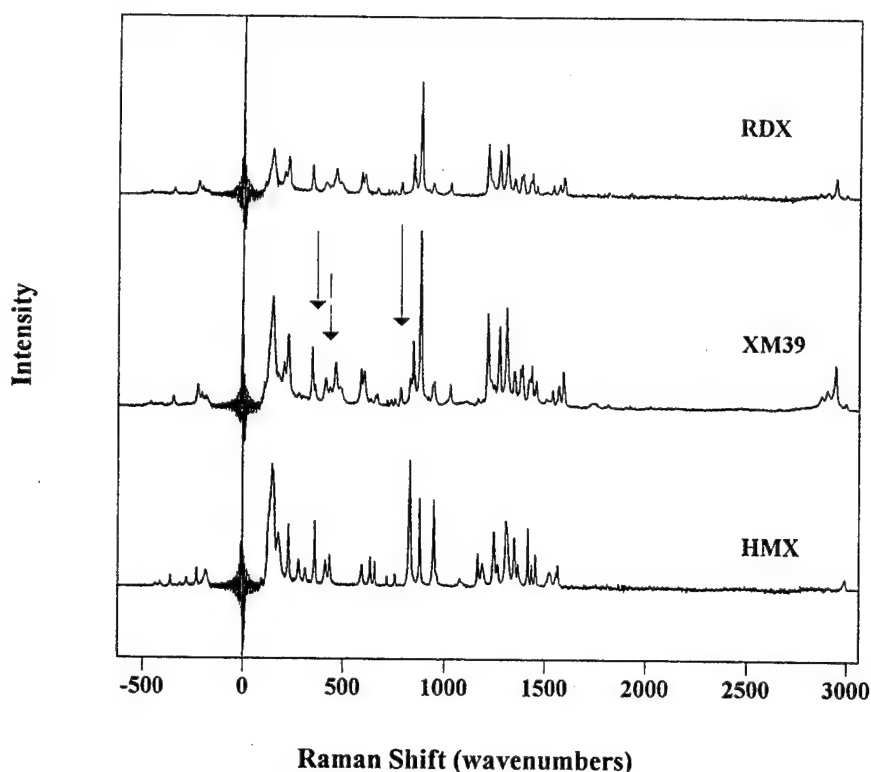


Figure 9. The Raman spectra of RDX, HMX, and XM39. Arrows indicate features in the spectrum of XM39 due to slight HMX "impurities" in domestically manufactured RDX.

Figure 10 shows the Raman spectra of RDX, XM39, and a commercially available propellant formulation believed to be manufactured in mainland China. Since the Chinese propellant formulation had a thin graphite coating that would cause the sample to absorb some of the incident laser radiation, the spectrum was measured by scattering the incident Nd:YAG laser radiation off of the surface of a spinning (2,400 rpm) 5-mm i.d. glass tube containing the propellant formulation. From Figure 10, it is apparent that the principal crystalline energetic material in the Chinese propellant formulation is RDX. Also, the spectrum of the Chinese propellant formulation shows no evidence of HMX, suggesting that the RDX present in the Chinese propellant formulation was manufactured by a different process than domestically produced RDX.

Figure 11 shows a portion of the Raman spectrum of the propellant formulation XM39 as it is heated from room temperature to the onset of decomposition at 458 K (185° C). This spectrum was measured by scattering the Nd:YAG laser light off the surface of a slice of XM39 taken from the interior of a propellant grain. As shown previously, the principal crystalline energetic ingredient in XM39 is RDX.

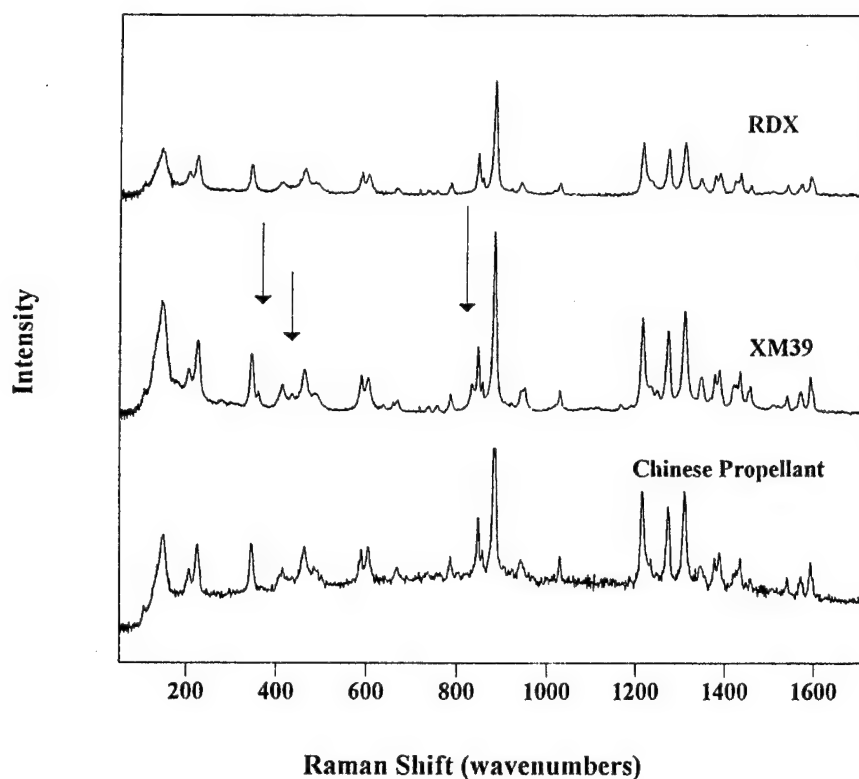


Figure 10. The FTR spectra of RDX, XM39, and a propellant formulation believed to have been manufactured in mainland China. Arrows indicate the presence of HMX in XM39.

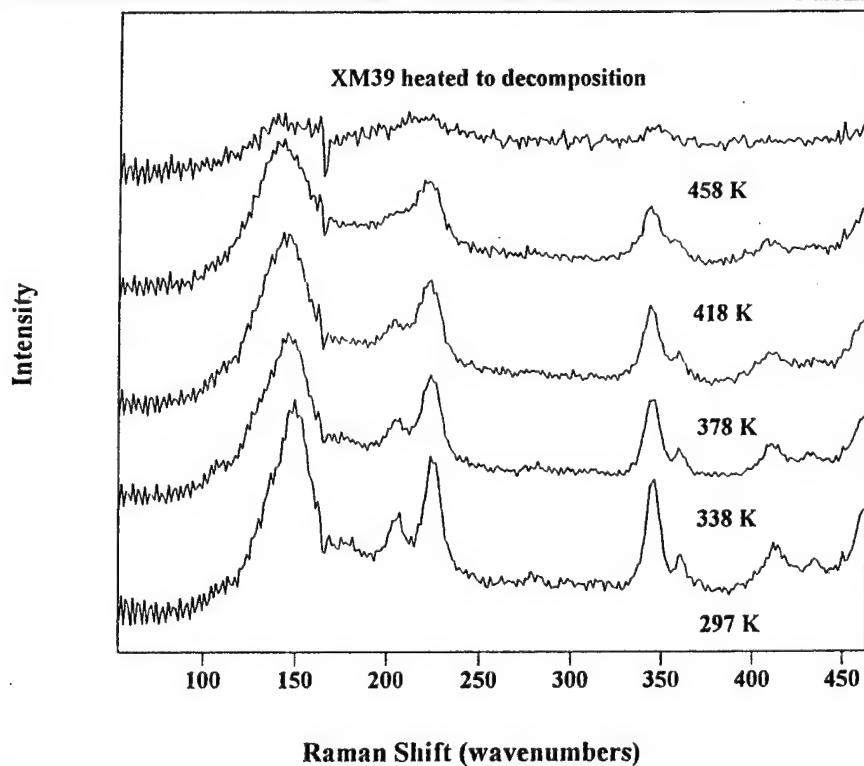


Figure 11. The FTR spectra of XM39 as it is heated from 297 K to 458 K. Note the slight red shift of the feature near 150  $\text{cm}^{-1}$ .

For XM39, as temperature is increased, the scattering intensity decreases (as shown by the decreased signal to noise ratio in the spectra) and there is a slight red shift of the feature near  $150\text{ cm}^{-1}$ . This red shift was most notable for features at low Raman frequencies, and was negligible at Raman frequencies above  $500\text{ cm}^{-1}$ . As the sample temperature approaches the melting point of RDX (477 K), the Raman intensity rapidly diminishes, reflecting a loss of crystallinity in the principal energetic ingredient in the formulation.

#### 4. CONCLUSION

It has been shown that FTR spectroscopy using NIR laser radiation as the scattering source can be a useful tool in characterizing many neat samples of energetic materials and of some propellant formulations. Raman spectra of some common energetic materials, as well as some newly formulated energetic materials, have been measured from  $100$  to  $3,000\text{ cm}^{-1}$ . To our knowledge, Raman spectra measured to within  $100\text{ cm}^{-1}$  of the Rayleigh line have not been reported for most energetic materials. Perhaps the most interesting result from our ability to measure Raman spectra over a wider spectral range is the observation that the most intense peak in the HMX spectrum occurs near  $150\text{ cm}^{-1}$ . Finally, we believe that for many samples of energetic materials containing crystalline principal ingredients, FTR spectroscopy using NIR laser scattering should be the preferred choice of investigators for forensic analysis when adequate sample is present. We are presently extending the technique to the investigation of energetic materials at elevated temperatures, in formulations, and in solutions.

**INTENTIONALLY LEFT BLANK.**

## 5. REFERENCES

- Akhaven, J. "Analysis of High Explosive Samples by Fourier Transform Raman Spectroscopy." Spectrochimica Acta. Part A, vol. 47, p. 1247, 1991.
- Goetz, F., and T. B. Brill. "Laser Raman Spectra of alpha-, beta-, gamma-, and delta-Octahydro-1,3,5,7-tetranito-1,3,5,7-tetrazocine and Their Temperature Dependence." Journal of Physical Chemistry. Vol. 83, p. 340, 1979.
- Griffith, P. R., and J. A. de Haseth. Fourier Transform Infrared Spectroscopy. New York: John Wiley & Sons, 1986.
- McNesby, K. L., J. E. Wolfe, J. B. Morris, and R. A. Pesce-Rodriguez. "Fourier Transform Raman Spectroscopy of Some Energetic Materials and Propellant Formulations." Journal of Raman Spectroscopy. Vol. 25, p. 75, 1994.

INTENTIONALLY LEFT BLANK.



<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	ADMINISTRATOR ATTN DTIC DDA DEFENSE TECHNICAL INFO CTR CAMERON STATION ALEXANDRIA VA 22304-6145

1	DIRECTOR ATTN AMSRL OP SD TA US ARMY RESEARCH LAB 2800 POWDER MILL RD ADELPHI MD 20783-1145
---	---

3	DIRECTOR ATTN AMSRL OP SD TL US ARMY RESEARCH LAB 2800 POWDER MILL RD ADELPHI MD 20783-1145
---	---

1	DIRECTOR ATTN AMSRL OP SD TP US ARMY RESEARCH LAB 2800 POWDER MILL RD ADELPHI MD 20783-1145
---	---

ABERDEEN PROVING GROUND

5	DIR USARL ATTN AMSRL OP AP L (305)
---	---------------------------------------

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	HQDA ATTN SARD TT DR F MILTON PENTAGON WASHINGTON DC 20310-0103
1	HQDA ATTN SARD TT MR J APPEL PENTAGON WASHINGTON DC 20310-0103
1	HQDA OASA RDA ATTN DR C H CHURCH PENTAGON ROOM 3E486 WASHINGTON DC 20310-0103
4	COMMANDER ATTN R GHIRARDELLI D MANN R SINGLETON R SHAW US ARMY RESEARCH OFFICE P O BOX 12211 RSCH TRNGLE PK NC 27709-2211
1	DIRECTOR ATTN AMXRO MCS K CLARK ARMY RESEARCH OFFICE P O BOX 12211 RSCH TRNGLE PK NC 27709-2211
1	DIRECTOR ATTN AMXRO RT IP LIB SERVICES ARMY RESEARCH OFFICE P O BOX 12211 RSCH TRNGLE PK NC 27709-2211
2	COMMANDER ATTN SMCAR AEE B D S DOWNS US ARMY ARDEC PCTNY ARSNL NJ 07806-5000
2	COMMANDER ATTN SMCAR AEE J A LANNON US ARMY ARDEC PCTNY ARSNL NJ 07806-5000
1	COMMANDER ATTN SMCAR AEE BR L HARRIS US ARMY ARDEC PCTNY ARSNL NJ 07806-5000

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	COMMANDER ATTN AMSMI RD PR E A R MAYKUT AMSMI RD PR P R BETTS US ARMY MISSILE COMMAND REDSTONE ARSENAL AL
1	OFFICE OF NAVAL RESEARCH DEPARTMENT OF THE NAVY ATTN R S MILLER CODE 432 800 N QUINCY STREET ARLINGTON VA 22217
1	COMMANDER ATTN J RAMNARACE AIR 54111C NAVAL AIR SYSTEMS COMMAND WASHINGTON DC 20360
2	COMMANDER ATTN R BERNECKER R 13 G B WILMOT R 16 NAVAL SURFACE WARFARE CENTER SILVER SPRING MD 20903-5000
5	COMMANDER ATTN M C LIN J MCDONALD E ORAN J SHNUR R J DOYLE CODE 6110 NAVAL RESEARCH LABORATORY WASHINGTON DC 20375
2	COMMANDER ATTN T BOGGS CODE 388 T PARR CODE 3895 NAVAL WEAPONS CENTER CHINA LAKE CA 93555-6001
1	SUPERINTENDENT ATTN D W NETZER DEPT OF AERONAUTICS NAVAL POSTGRADUATE SCHOOL MONTEREY CA 93940
3	AL LSCF ATTN R CORLEY R GEISLER J LEVINE EDWARDS AFB CA 93523-5000

NO. OF  
COPIES   ORGANIZATION

1   AFOSR  
ATTN J M TISHKOFF  
BOLLING AIR FORCE BASE  
WASHINGTON DC 20332

1   OSD SDIO IST  
ATTN L CAVENY  
PENTAGON  
WASHINGTON DC 20301-7100

1   COMMANDANT  
ATTN ATSF TSM CN  
USAFAS  
FORT SILL OK 73503-5600

1   UNIV OF DAYTON RSCH INSTITUTE  
ATTN D CAMPBELL  
AL PAP  
EDWARDS AFB CA 93523

1   NASA  
ATTN G B NORTHAM MS 168  
LANGLEY RESEARCH CENTER  
LANGLEY STATION  
HAMPTON VA 23365

4   NATIONAL BUREAU OF STANDARDS  
ATTN J HASTIE  
M JACOX  
T KASHIWAGI  
H SEMERJIAN  
US DEPARTMENT OF COMMERCE  
WASHINGTON DC 20234

2   DIRECTOR  
ATTN C WESTBROOK  
W TAO MS L 282  
LAWRENCE LIVERMORE NATIONAL LAB  
P O BOX 808  
LIVERMORE CA 94550

1   DIRECTOR  
ATTN B NICHOLS T7 MS B284  
LOS ALAMOS NATIONAL LAB  
P O BOX 1663  
LOS ALAMOS NM 87545

1   NATIONAL SCIENCE FOUNDATION  
ATTN A B HARVEY  
WASHINGTON DC 20550

NO. OF  
COPIES   ORGANIZATION

2   PRINCETON COMBUSTION  
RESEARCH LABORATORIES INC  
ATTN N A MESSINA  
M SUMMERFIELD  
PRINCETON CORPORATE PLAZA  
BLDG IV SUITE 119  
11 DEERPARK DRIVE  
MONMOUTH JUNCTION NJ 08852

3   DIRECTOR  
DIVISION 8354  
ATTN S JOHNSTON  
P MATTERN  
D STEPHENSON  
SANDIA NATIONAL LABORATORIES  
LIVERMORE CA 94550

1   BRIGHAM YOUNG UNIVERSITY  
ATTN M W BECKSTEAD  
DEPT OF CHEMICAL ENGINEERING  
PROVO UT 84058

1   CALIFORNIA INSTITUTE OF TECH  
JET PROPULSION LABORATORY  
ATTN L STRAND MS 125 224  
4800 OAK GROVE DRIVE  
PASADENA CA 91109

1   CALIFORNIA INSTITUTE OF TECHNOLOGY  
ATTN F E C CULICK MC 301 46  
204 KARMAN LAB  
PASADENA CA 91125

1   UNIVERSITY OF CALIFORNIA  
LOS ALAMOS SCIENTIFIC LAB  
P O BOX 1663 MAIL STOP B216  
LOS ALAMOS NM 87545

1   UNIVERSITY OF CALIFORNIA BERKELEY  
CHEMISTRY DEPARMENT  
ATTN C BRADLEY MOORE  
211 LEWIS HALL  
BERKELEY CA 94720

1   UNIVERSITY OF CALIFORNIA SAN DIEGO  
ATTN F A WILLIAMS  
AMES B010  
LA JOLLA CA 92093

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	UNIV OF CALIFORNIA SANTA BARBARA QUANTUM INSTITUTE ATTN K SCHOFIELD M STEINBERG SANTA BARBARA CA 93106
1	UNIV OF COLORADO AT BOULDER ENGINEERING CENTER ATTN J DAILY CAMPUS BOX 427 BOULDER CO 80309-0427
3	UNIV OF SOUTHERN CALIFORNIA DEPT OF CHEMISTRY ATTN R BEAUDET S BENSON C WITTIG LOS ANGELES CA 90007
1	CORNELL UNIVERSITY DEPARTMENT OF CHEMISTRY ATTN T A COOL BAKER LABORATORY ITHACA NY 14853
1	UNIVERSITY OF DELAWARE ATTN T BRILL CHEMISTRY DEPARTMENT NEWARK DE 19711
1	UNIVERSITY OF FLORIDA ATTN J WINEFORDNER DEPT OF CHEMISTRY GAINESVILLE FL 32611
3	GEORGIA INSTITUTE OF TECHNOLOGY SCHOOL OF AEROSPACE ENGINEERING ATTN E PRICE W C STRAHLE B T ZINN ATLANTA GA 30332
1	UNIVERSITY OF ILLINOIS DEPT OF MECH ENG ATTN H KRIER 144MEB 1206 W GREEN ST URBANA IL 61801
1	THE JOHNS HOPKINS UNIV CPIA ATTN T W CHRISTIAN 10630 LITTLE PATUXENT PKWY SUITE 202 COLUMBIA MD 21044-3200

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	UNIVERSITY OF MICHIGAN GAS DYNAMICS LAB ATTN G M FAETH AEROSPACE ENGINEERING BLDG ANN ARBOR MI 48109-2140
1	UNIVERSITY OF MINNESOTA DEPT OF MECHANICAL ENGINEERING ATTN E FLETCHER MINNEAPOLIS MN 55455
4	PENNSYLVANIA STATE UNIVERSITY DEPT OF MECHANICAL ENGINEERING ATTN K KUO M MICCI S THYNELL V YANG UNIVERSITY PARK PA 16802
1	POLYTECHNIC INSTITUTE OF NY GRADUATE CENTER ATTN S LEDERMAN ROUTE 110 FARMINGDALE NY 11735
2	PRINCETON UNIVERSITY FORRESTAL CAMPUS LIBRARY ATTN K BREZINSKY I GLASSMAN P O BOX 710 PRINCETON NJ 08540
1	PURDUE UNIVERSITY SCHOOL OF AERONAUTICS AND ASTRONAUTICS ATTN J R OSBORN GRISSOM HALL WEST LAFAYETTE IN 47906
1	PURDUE UNIVERSITY DEPARTMENT OF CHEMISTRY ATTN E GRANT WEST LAFAYETTE IN 47906
2	PURDUE UNIVERSITY SCHOOL OF MECHANICAL ENGINEERING ATTN N M LAURENDEAU S N B MURTHY TSPC CHAFFEE HALL WEST LAFAYETTE IN 47906

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	RENSSELAER POLYTECHNIC INST DEPT OF CHEMICAL ENGINEERING ATTN A FONTIJN TROY NY 12181	1	EXXON RESEARCH & ENG CO ATTN A DEAN ROUTE 22E ANNANDALE NJ 08801
1	STANFORD UNIVERSITY DEPT OF MECHANICAL ENGINEERING ATTN R HANSON STANFORD CA 94305	1	GENERAL APPLIED SCIENCE LABS INC 77 RAYNOR AVENUE RONKONKAMA NY 11779-6649
1	UNIVERSITY OF TEXAS DEPT OF CHEMISTRY ATTN W GARDINER AUSTIN TX 78712	1	GENERAL ELECTRIC ORDNANCE SYSTEMS ATTN J MANDZY 100 PLASTICS AVENUE PITTSFIELD MA 01203
1	VA POLYTECH INST AND STATE UNIV ATTN J A SCHETZ BLACKSBURG VA 24061	1	GENERAL MOTORS RSCH LABS PHYSICAL CHEMISTRY DEPARTMENT ATTN T SLOANE WARREN MI 48090-9055
1	APPLIED COMBUSTION TECHNOLOGY INC ATTN A M VARNEY P O BOX 607885 ORLANDO FL 32860	2	HERCULES INC ATTN W B WALKUP E A YOUNT P O BOX 210 ROCKET CENTER WV 26726
2	APPLIED MECHANICS REVIEWS ASME ATTN R E WHITE & A B WENZEL 345 E 47TH STREET NEW YORK NY 10017	1	HERCULES INC ATTN R V CARTWRIGHT 100 HOWARD BLVD KENVIL NJ 07847
1	ATLANTIC RESEARCH CORP ATTN R H W WAESCHE 7511 WELLINGTON ROAD GAINESVILLE VA 22065	1	ALLIANT TECHSYSTEMS INC MARINE SYSTEMS GROUP ATTN D E BRODEN MS MN50 2000 600 2ND STREET NE HOPKINS MN 55343
1	TEXTRON DEFENSE SYSTEMS ATTN A PATRICK 2385 REVERE BEACH PARKWAY EVERETT MA 02149-5900	1	ALLIANT TECHSYSTEMS INC ATTN R E TOMPKINS MN 11 2720 600 SECOND ST NORTH HOPKINS MN 55343
1	BATTELLE TWSTIAC 505 KING AVENUE COLUMBUS OH 43201-2693	1	IBM CORPORATION ATTN A C TAM RESEARCH DIVISION 5600 COTTLE ROAD SAN JOSE CA 95193
1	COHEN PROFESSIONAL SERVICES ATTN N S COHEN 141 CHANNING STREET REDLANDS CA 92373	1	IIT RESEARCH INSTITUTE ATTN R F REMALY 10 WEST 35TH STREET CHICAGO IL 60616

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	LOCKHEED MISSILES & SPACE CO ATTN GEORGE LO 3251 HANOVER STREET DEPT 52 35 B204 2 PALO ALTO CA 94304
1	OLIN ORDNANCE ATTN V MCDONALD LIBRARY P O BOX 222 ST MARKS FL 32355-0222
1	PAUL GOUGH ASSOCIATES INC ATTN P S GOUGH 1048 SOUTH STREET PORTSMOUTH NH 03801-5423
1	HUGHES AIRCRAFT COMPANY ATTN T E WARD 8433 FALLBROOK AVENUE CANOGA PARK CA 91303
1	ROCKWELL INTERNATIONAL CORP ROCKETDYNE DIVISION ATTN J E FLANAGAN HB02 6633 CANOGA AVENUE CANOGA PARK CA 91304
1	SCIENCE APPLICATIONS INC ATTN R B EDELMAN 23146 CUMORAH CREST WOODLAND HILLS CA 91364
3	SRI INTERNATIONAL ATTN G SMITH D CROSLEY D GOLDEN 333 RAVENSWOOD AVENUE MENLO PARK CA 94025
1	STEVENS INSTITUTE OF TECH DAVIDSON LABORATORY ATTN R MCALEVY III HOBOKEN NJ 07030
1	SVERDRUP TECHNOLOGY INC LERC GROUP ATTN R J LOCKE MS SVR 2 2001 AEROSPACE PARKWAY BROOK PARK OH 44142

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	SVERDRUP TECHNOLOGY INC ATTN J DEUR 2001 AEROSPACE PARKWAY BROOK PARK OH 44142
3	THIOKOL CORPORATION ELKTON DIVISION ATTN R BIDDLE R WILLER TECH LIB P O BOX 241 ELKTON MD 21921
3	THIOKOL CORPORATION WASATCH DIVISION ATTN S J BENNETT P O BOX 524 BRIGHAM CITY UT 84302
1	UNITED TECHNOLOGIES RSCH CENTER ATTN A C ECKBRETH EAST HARTFORD CT 06108
1	UNITED TECHNOLOGIES CORP CHEMICAL SYSTEMS DIVISION ATTN R R MILLER P O BOX 49028 SAN JOSE CA 95161-9028
1	UNIVERSAL PROPULSION COMPANY ATTN H J MCSPADDEN 25401 NORTH CENTRAL AVENUE PHOENIX AZ 85027-7837
1	VERITAY TECHNOLOGY INC ATTN E B FISHER 4845 MILLERSPORT HIGHWAY EAST AMHERST NY 14051-0305
1	FREEDMAN ASSOCIATES ATTN E FREEDMAN 2411 DIANA ROAD BALTIMORE MD 21209-1525
1	ALLIANT TECHSYSTEMS ATTN J BODE 600 SECOND ST NE HOPKINS MN 55343

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	ALLIANT TECHSYSTEMS ATTN C CANDLAND 600 SECOND ST NE HOPKINS MN 55343
1	ALLIANT TECHSYSTEMS ATTN L OSGOOD 600 SECOND ST NE HOPKINS MN 55343
1	ALLIANT TECHSYSTEMS ATTN R BURETTA 600 SECOND ST NE HOPKINS MN 55343
1	ALLIANT TECHSYSTEMS ATTN R BECKER 600 SECOND ST NE HOPKINS MN 55343
1	ALLIANT TECHSYSTEMS ATTN M SWENSON 600 SECOND ST NE HOPKINS MN 55343
1	US ARMY BENET LABORATORY ATTN SAM SOPOK SMCAR CCB B WATERVLIET NY 12189

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
	<u>ABERDEEN PROVING GROUND</u>
36	DIR USARL ATTN: AMSRL-WT-P, A HORST AMSRL-WT-PC, R A FIFER G F ADAMS W R ANDERSON R A BEYER S W BUNTE C F CHABALOWSKI K P MC-NEILL BOONSTOPPEL A COHEN R CUMPTON R DANIEL D DEVYNCK N F FELL B E FORCH J M HEIMERL A J KOTLAR M R MANAA W F MCBRATNEY K L MCNESBY S V MEDLIN M S MILLER A W MIZIOLEK S H MODIANO J B MORRIS J E NEWBERRY S A NEWTON R A PESCE-RODRIGUEZ B M RICE R C SAUSA M A SCHROEDER J A VANDERHOFF M WENSING A WHREN J M WIDDER C WILLIAMSON AMSRL-CI-CA, R PATEL

INTENTIONALLY LEFT BLANK.



## USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number ARL-TR-843 Date of Report August 1995
2. Date Report Received \_\_\_\_\_
3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_
4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_
5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_
6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

CURRENT  
ADDRESS

\_\_\_\_\_  
Organization

\_\_\_\_\_  
Name

\_\_\_\_\_  
Street or P.O. Box No.

\_\_\_\_\_  
City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD  
ADDRESS

\_\_\_\_\_  
Organization

\_\_\_\_\_  
Name

\_\_\_\_\_  
Street or P.O. Box No.

\_\_\_\_\_  
City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)  
(DO NOT STAPLE)

---

DEPARTMENT OF THE ARMY

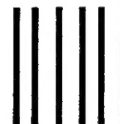
OFFICIAL BUSINESS

**BUSINESS REPLY MAIL**

FIRST CLASS PERMIT NO 0001,APG,MD

POSTAGE WILL BE PAID BY ADDRESSEE

DIRECTOR  
U.S. ARMY RESEARCH LABORATORY  
ATTN: AMSRL-WT-PC  
ABERDEEN PROVING GROUND, MD 21005-5066



NO POSTAGE  
NECESSARY  
IF MAILED  
IN THE  
UNITED STATES

